Limitation to WDM Transmission Distance due to Cross-Phase Modulation Induced Spectral Broadening in Dispersion Compensated Standard Fiber Systems

V. Mikhailov, R. I. Killey, J. Prat, and P. Bayvel, *Member, IEEE*

***Abstract*— We describe large spectral broadening due to the interaction of cross-phase modulation/self-phase modulation and fiber dispersion, and explain its contribution to the penalties in standard fiber systems pre- and postcompensated by dispersion compensating fiber. To our knowledge, this is the first measurement of this effect in a dense WDM transmission system at 10 Gb/s with this dispersion management scheme and good agreement is reported with the numerical modeling results.**

***Index Terms*—Optical communication, optical fiber nonlinearities, wavelength-division multiplexing.**

I. Introduction

MULTIWAVELENGTH transmission systems with increasing number of channels and longer interamplifier spans require necessarily higher powers per channel to maintain acceptable signal-to-noise ratios (SNR's) [1]. In these systems, the transmission distances will be limited mainly by fiber nonlinearities including cross-phase modulation (XPM) [2] and self-phase modulation (SPM). In dispersion-compensated, standard single-mode fiber (SSMF, $D = +17$ ps/nm/km), the high fiber dispersion converts the induced nonlinear SPM/XPM into amplitude modulation, and results in signal distortion, which increases with bit rate [3]. We have recently reported on how optimization of the dispersion map minimizes the performance limitations due to these effects, allowing the transmission distance to be extended [4], [5]. In particular we have shown that at high channel powers (4–11 dBm/channel), precompensation can significantly improve dense WDM transmission at 10 Gb/s, although significant penalties were still obtained with channel powers >4 dBm/channel. In this letter, we report new results explaining the source of the power penalties in pre- and postcompensated SSMF systems. A new technique using a gated, high-resolution, all-fiber scanning Fabry–Perot (FP) interferometer allowed the direct measurement of spectral broadening in pre- and postcompensated transmission in a recirculating fiber loop. To the best of our knowledge, this is the first measurement of large spectral broadening due to XPM with precompensation and provides a clear explanation of the observed penalties at high channel powers.

Manuscript received February 26, 1999; revised April 12, 1999. This work was supported by the Royal Society and by the U.K. Engineering and Physical Sciences Research Council. B. Mikhailov was supported by fellowships from the University of London Central Research Fund and UCL Graduate School,

V. Mikhailov, R. I. Killey, and P. Bayvel are with the Optical Networks Group, Department of Electronic and Electrical Engineering, University College London, Torrington Place, London WC1E 7JE, U.K.

J. Prat is with the Department of Signal Theory and Communications, Universitat Politècnica de Catalunya, 08034 Barcelona, Spain.

Publisher Item Identifier S 1041-1135(99)05902-9.

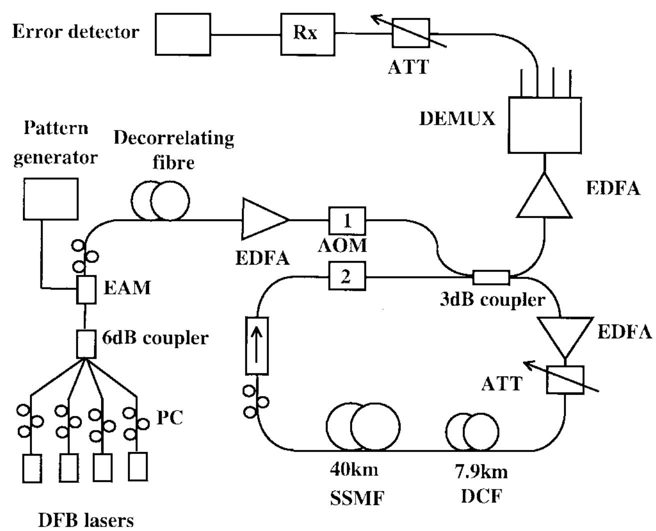
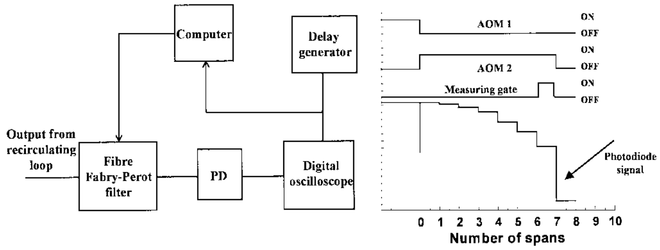


Fig. 1. Optical fiber recirculating loop setup.

II. Experimental Setup

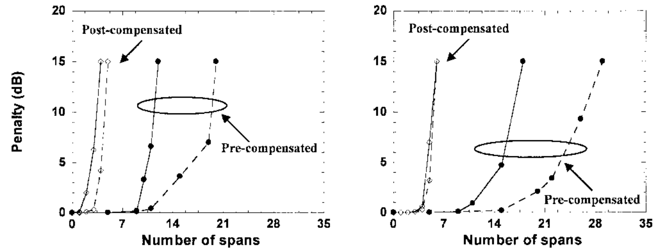
The recirculating loop configuration [5] is shown in Fig. 1. The loop consisted of a 40-km span of Corning SSMF ($\alpha = 0.23$ dB/km), exactly post- or precompensated by two spools of 3.95-km Corning dispersion compensating fiber (DCF) ($D = -87.3$ ps/nm/km, $\alpha = 0.49$ dB/km, DCF/SSMF splice loss 0.7 dB), acoustooptic modulators (AOM), and a 3 dB coupler, with a total loop loss of 21 dB. This loss was compensated by a Corning gain-flattened EDFA with a saturated output power of +16 dBm and a noise figure of 4.5 dB.

Four DFB lasers, equally spaced by 50 GHz (0.4 nm) in the range 1556.4 nm (Channel 1) to 1557.6 nm (Channel 4), were multiplexed by a 4×4 coupler, modulated using an electroabsorption modulator (EAM) with a 10-Gb/s NRZ pseudorandom pattern, and decorrelated using 10.5 km of SSMF or the same amount of SSMF with 3.8 km of DCF



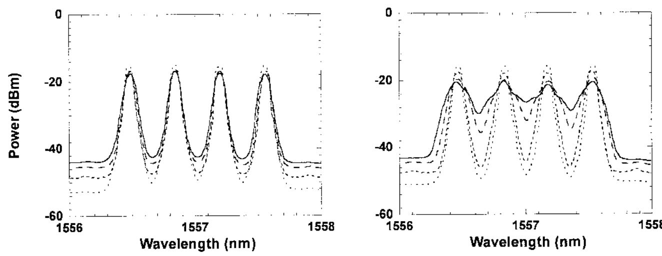
(a) (b)

Fig. 2. Gated scanning FP filter for (a) high-resolution optical spectral measurements and (b) timing diagrams of the photodiode signal and delay generator outputs.



(a) (b)

Fig. 3. Experimental penalty curves for post-(diamonds) and pre-(circles) compensated systems with +8 dBm (left) and +4 dBm (right) per channel; single channel (dashed lines) and four channels (solid lines).



(a) (b)

Fig. 4. Optical spectra at output of loop, back-to-back, 4, 8, and 12 recirculations, measured using an optical spectrum analyzer (OSA). For both postcompensated (left) and precompensated (right) cases, the value and sign of the decorrelator was chosen to give comparable pulse walkthrough.

($D = -94$ ps/nm/km). The input power to the decorrelating fiber (DF) was -10 dBm/channel avoiding nonlinear effects.

The input power to the fiber span was varied in the range +4 to +8 dBm/channel. The same state of polarization was set for all channels to minimize the polarization-dependent loss. The signal was demultiplexed using a high-resolution, tunable concave grating with crosstalk lower than -25 dB for 50-GHz channel spacing followed by an optically preamplified receiver and error detector.

The spectra of the transmitted channels were measured using either a conventional optical spectrum analyzer (0.65-Å resolution) or a high-resolution scanning Micron Optics FP filter with a finesse of 600 and a free-spectral range of 150 GHz, giving a 2-pm resolution. To operate the scanning FP with the recirculating loop setup, the gating scheme shown in Fig. 2 was realized. The filter was connected through the photodetector to the digital sampling scope (DSS). The second channel of the DSS was connected to the gate output of the delay generator controlling the loop. The gating pulses were used to select the part of the transmitted signal that had propagated the desired number of recirculations. During the measurements the filter was tuned by the computer within the specified wavelength span in 2-pm steps. At each wavelength, the section of the photodiode signal measured at the same time as the gate pulse was transfered to the computer and the mean value of the signal calculated by the software.

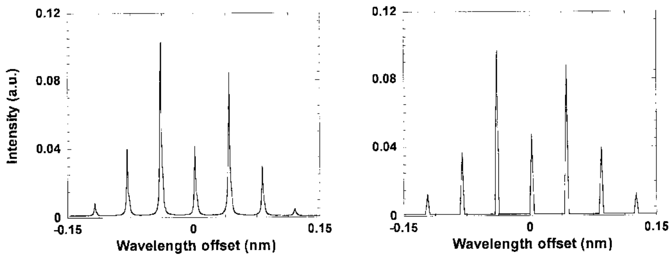
III. Results and Discussion

Single channel and four-channel transmission experiments were performed for both pre-(DCF+SSMF) and post-(SSMF+DCF) compensation schemes for a range of channel powers. The measured power penalties with the number of recirculations are shown in Fig. 3. Initially, single channel 10-Gb/s experiments were performed, to investigate the effect of SPM alone. For the precompensated link a transmission distance of more than 20 and 15 spans (>1000 km) was achieved before a 3-dB penalty (BER $= 10^{-9}$) was reached for the input powers +4 and +8 dBm, respectively. These distances were reduced by a factor of four for the postcompensated link. The eye closure was much more severe in the postcompensated case. With postcompensation, the SPM chirp acquired in the SSMF leads to additional pulse broadening in the negative dispersion of the DCF, and hence eye closure [4], [5]. The reverse occurs in the precompensated case, were the SPM chirp acts to compress the pulses in the SSMF at the end of each span.

The dual-stage EDFA's with DCF between the stages can be used to minimize launched power into the fibers [1], although this increases complexity in system design. Also eye opening resulting from SPM in the DCF placed after the EDFA can reduce penalties.

Next, experiments with four channels spaced by 50 GHz, the same power per channel and 10.5-km SSMF decorrelator were carried out. Little change in the penalty compared to the single-channel case was observed for the postcompensated experiment, as expected, since SPM-induced temporal pulse broadening is dominant. However, the presence of neighboring channels in the precompensated WDM experiments resulted in a reduction of the maximum possible transmission distance to less than 10 spans. This is attributed to two causes. Firstly, the XPM-induced timing jitter results from the reduced length of the compressed pulse. In dispersion-compensated schemes, the phase shift induced by XPM distributed along the length of the nonlinear fiber leads to intensity distortion due to the residual dispersion at the end of the span. Secondly, increasing crosstalk occurs between channels at the receiver due to spectral broadening [6] caused by XPM and SPM leading to the transfer of spectral components from one channel into the bandwidth of neighboring channels. The same effect was previously observed in nonzero dispersion-shifted fiber transmission experiments [7].

To investigate the level of this crosstalk, the spectra of the WDM signals were measured after 1, 4, 8, and 12 recircu-



(a) (b)

Fig. 5. Optical spectra of channel 2 after 12 spans with precompensation: Experimental (left), measured with a gated scanning FP filter and corresponding simulated spectrum (right). Carrier wavelength is at 0-nm offset.

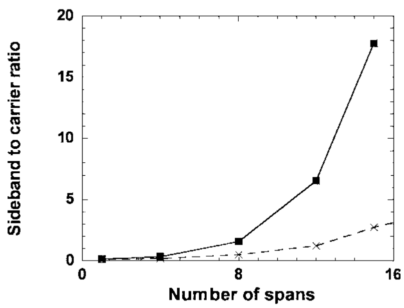


Fig. 6. Experimentally measured increase in sideband-to-carrier power ratio with distance for single channel (dashed) and channel 2 in a four-channel experiment (solid).

lations of the loop using the optical spectrum analyzer and the gated scanning FP filter. Large spectral broadening with transmission distance was observed, as shown recorded with an optical spectrum analyzer in Fig. 4. This occurs in the case of precompensation as a result of the compressed pulses at the start of each span leading to large SPM and XPM. The effect of XPM is maximized when pulses in neighboring channels are aligned in the nonliner fiber. Simulations predicted that the time averaged effects are reduced as the signals become decorrelated and this trend was confirmed with the use of SSMF + DCF decorrelator. However, even for decorrelated channels, the occurrence of pulses aligned in a number of channels will result in their increased distortion.

The broader pulses in the postcompensated configuration resulted in low spectral broadening for both DF's.

The high-resolution gated FP spectrum measured for channel 2 at $+8$ dBm/channel with $1010\cdots$bit pattern after 12 spans is shown in Fig. 5. The spectrum calculated by solving the nonlinear Schrödinger equation using the split-step Fourier method is also shown and is in close agreement with the experiments.

The resultant power transfer from the carrier to the sidebands as a function of the number of spans is plotted in Fig. 6, showing the SPM-induced broadening (single channel) and additional broadening due to XPM with the four transmitted channels.

IV. Conclusion

We report new results explaining the nature of transmission penalty in 50-GHz spaced WDM transmission over standard fiber, pre- and postcompensated with DCF at 10 Gb/s. In particular, at power levels of 4–8 dBm/channel, precompensation allows significantly longer transmission distance. This can be explained by the pulse compression, rather than pulse broadening which occurs with postcompensation. However, precompensation is also accompanied by spectral broadening and jitter which eventually limit the transmission distance. Accurate measurements and simulations of the optical spectra have shown that coherent crosstalk at the receiver, due to XPM- and SPM-induced spectral broadening, can be a main source of penalty in precompensated DWDM transmission. The increased coherent crosstalk between spectral components of neighboring channels, broadened by fiber nonlinearity, is the dominant mechanism explaining the increase in the penalties measured in the multichannel experiments.

Acknowledgment

The authors would like to thank Corning Inc. (A. Evans and D. Hall), Hewlett-Packard Ipswich components operation (C. Park), and Nortel (I. Hardcastle) for the loan of equipment.

References

[1] S. Bigo, A. Bertaina, M. Chbat, S. Gurib, J. DaLoura, J. C. Jacquinot, J. Hervo, P. Bousselet, S. Borne, D. Bayart, L. Gasca, and J. L. Beylat, "320 Gbit/s WDM transmission over 500 km of conventional single-mode fiber with 125 km amplifier spacing," in *Proc. ECOC'97*, vol. 5, pp. 17–20, postdeadline papers.
[2] N. Kikuchi, K. Sekine, and S. Sasaki, "Analysis of cross-phase modulation (XPM) effect on WDM transmission performance," *Electron. Lett.*, vol. 33, p. 653, 1997.
[3] H.-J. Thiele, R. I. Killey, and P. Bayvel, "Influence of fiber dispersion and bit-rate on XPM-induced distortion in amplified optical fiber links," *Electron. Lett.*, vol. 34, Oct. 1998.
[4] D. M. Rothnie and J. E. Midwinter, "Improved standard-fiber performance by positioning dispersion compensating fiber," *Electron. Lett.*, vol. 32, p. 1907, 1996.
[5] V. N. Mikhailov, H. J. Thiele, R. I. Killey, and P. Bayvel, "Opimization of WDM transmission of multi-10 Gbit/s, 50 GHz-spaced channels, over standard fiber," in *Proc. ECOC'98*, Madrid, Spain, vol. 1, Sept. 1998, pp. 595–596.
[6] V. N. Mikhailov, R. Killey, J. Pratt, and P. Bayvel, "Measurement of penalty due to cross-phase modulation induced spectral broadening in dispersion-compensated standard-fiber dense WDM transmission," to be presented at *CLEO'99*.
[7] M. Eiselt, R. D. Garrett, and R. W. Tkach, "Experimental comparison of WDM system capacity in conventional and nonzero dispersion shifted fiber," *IEEE Photon. Technol. Lett.*, vol. 11, pp. 281–283, Feb. 1999.